Soil of the Intensive Agriculture Biome of Biosphere 2

by

H. Allen Torbert and Hyrum B. Johnson

Allen Torbert is a soil scientist with the USDA-ARS (U.S. Department of Agriculture—Agricultural Research Service) with the Natural Resources Systems Research Unit at the Grassland Soil and Water Research Laboratory, Temple, Texas. Hyrum Johnson is an ecologist with the USDA-ARS (U.S. Department of Agriculture—Agricultural Research Service)with the Grassland Protection Research Unit at the Grassland Soil and Water Research Laboratory, Temple Texas.

Biosphere 2, located in Oracle, Arizona, is an impressive structure designed as a closed system for several ecosystems, including a rainforest, desert, savanna, marsh, ocean, and a separate agriculture area designated as the Intensive Agriculture Biome (IAB) (Figure 1). The synthetic communities of plants and soils are enclosed in a glass and metal shell that encompasses 1.28 ha, and is internationally known for its beauty and sophisticated environmental control capacity.

Originally undertaken as a commercial venture, Biosphere 2 was designed as a prototype for a Mars space station with a materially closed ecological system that could maintain equilibrium and sustain life support for human beings over long periods of time. This remarkable facility sealed a volume of approximately 180,000 m^3 with a leak rate measured at 6% per year (Nelson et al. 1993). However, Biosphere 2 came under attack by some in the science community for lack of rigor (Kaiser 1996) and for controversial promotional tactics. Following difficulty in growing sufficient food and a secretive attempt to inject O_2 to correct an unexpected O_2 depletion in the Biosphere 2 atmosphere, the facility became labeled as a "New Age" stunt (Wolfgang 1995; Rabinovitz 1995). Biosphere 2 came to be viewed as a scientific joke, and even became the subject of a movie spoof (Holden 1996). At the center of the Biosphere 2 problems was organically enriched soil, which led to excessively high soil respiration rates resulting in atmospheric CO_2 enrichment and O_2 depletion (Severinghaus et al. 1994).

Presently under the new management of Columbia University, Biosphere 2 is seeking to establish a scientific reputation by utilizing the complex as a state-of-the-art research and educational facility for environmental sciences (Wolfgang 1995; Rabinovitz 1995). Biosphere 2 presents a unique opportunity to examine the impacts of global change on plant growth and soil properties by allowing examination of changes in plant and soil due to atmospheric treatments under field-scale conditions. In addition, this facility will also allow for realistic manipulation of plant residues and maintenance of the atmospheric and climatic conditions year round. But one vital question still remains: What about the soil?

The objective of this study was to examine the soil of the intensive agriculture biome (IAB), not only to determine its suitability for continued research, but also to determine what can be learned about soil process dynamics from the elevated atmospheric CO_2 conditions that have been present in the Biosphere 2 since closure.

Biosphere's History

Biosphere 2 is an unique structure that is a model of the earth's biosphere, materially isolated from the outside environment. The entire structure encompassed approximately 1.28 ha in a volume of 180,000 m^3, which is thought to be the largest closed system on earth. The structure was completed in 1991 and was sealed from September 1991 to March 1995. During this time, there were two high profile missions in which people lived within the sealed Biosphere 2 (Broecker 1996). During these missions, the biospherians inside sustained all of their nutritional needs from the plants and animals that they produced in the IAB. However, Biosphere 2 experienced several physical and managerial problems that surrounded the entire operation in controversy and drama. The physical problems experienced included an initial difficulty in growing many of the crop plants planned for food production [including an initial failure of corn (*Zea mays* L) and low yielding rice (*Oryza sativa* L) production], an unexpected rise in CO_2 levels and an even more drastic O_2 depletion in the Biosphere 2 atmosphere.

During the period of closure, the O_2 content of the atmosphere in Biosphere 2 steadily declined from the initial 21%, losing an average 1000 mol O_2 each day (Broecker 1996). By January 1992, the atmospheric O_2 content had reached 14%, so truck loads of liquid O_2 were pumped into the sealed Biosphere 2 to maintain the atmospheric O_2 content at safe levels. This practice continued through January 1995 when N_2O concentration of the Biosphere 2 atmosphere reached dangerous levels. At that time, the operation of Biosphere 2 was switched to a flow through mode, and the structure was ven-

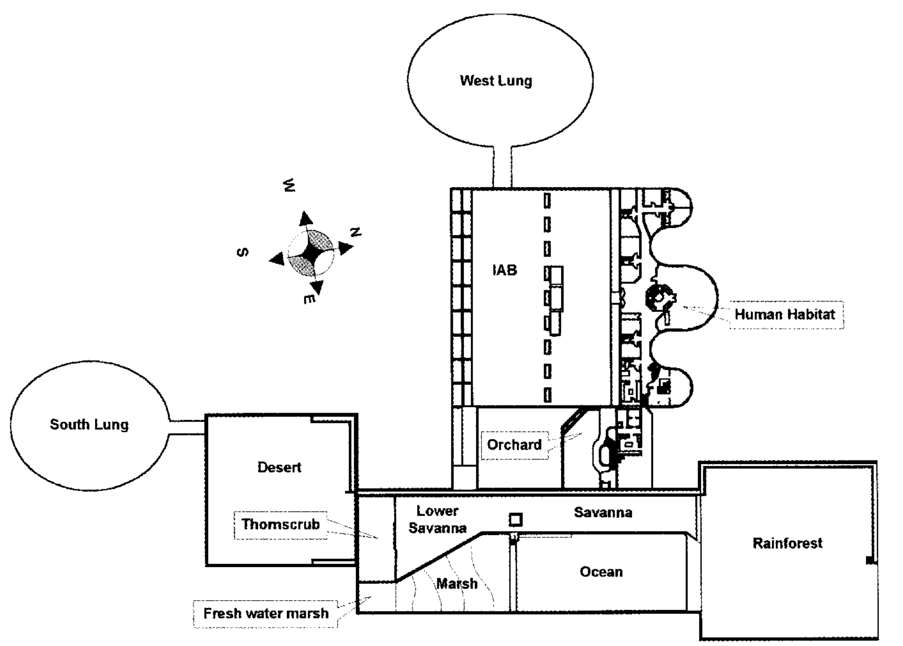


Figure 1. A floor map of Biosphere 2, showing the biomes in the "wilderness area," the intensive agriculture biome (IAB), and the human habitat.

tilated with air from the outside atmosphere. The mystery of the elevated CO_2 rise and O_2 depletion was solved by scientists at Columbia University (Broecker 1996) who traced the problems primarily to the soils in the IAB and the curing of the Biosphere 2 structure's concrete.

The Biosphere 2 planners, knowing that the IAB would have to produce all of the food for the biospherians inside without the use of additional fertilizer application, strove to provide the richest soil possible. Consequently, the soil bed was filled to a depth of 1.2 m with a base soil and organic matter mixture. The base soil of the IAB was excavated from a nearby area know as "Wilson's Pond," which was a sedimentation area behind an earthen dam constructed as a watering hole for cattle. Organic matter in the form of peat moss and compost were mixed with soil at a rate of 15% peat moss, 15% compost, and 60% Wilson Pond soil by volume. The soil loading preceded carefully with a good uniform mixture applied throughout the soil bed. The true mass proportion of soil to organic matter addions can not be calculated because volume and mass relationships among the soil and the amendments used can be quite different. They depend on handling and moisture and can change significantly on settling, the true mass proportion of soil to organic matter additions can not be calculated.

Microbial respiration during decomposition of this organically enriched soil increased CO_2 production and O_2 consumption many times greater than could be assimilated by plants during photosynthesis, resulting in a large increase in the CO_2 concentration in the Biosphere 2 atmosphere. Surprisingly, the level of the CO_2 rise was not proportional to the O_2 depletion. It was was eventually realized that a large proportion of the CO_2 was being adsorbed by the curing concrete, converting $Ca(OH)_2$ to $CaCO_3$ (Severinghaus et al. 1994).

Regardless of the previous controversies and drama, Biosphere 2 offers an unique opportunity for the scientific study of ecological systems. In January 1996, Columbia University assumed management responsibility. At that point, two major structural changes to the Biosphere 2 were undertaken. First, the wilderness biome, the IAB, and human habitat were isolated from each other. The human habitat area was converted into a state-of-the-art science museum. The IAB has been subdivided into three separate areas, or bays, that can be independently controlled for atmospheric and climate conditions (renamed the Agro-Forestry Biome).

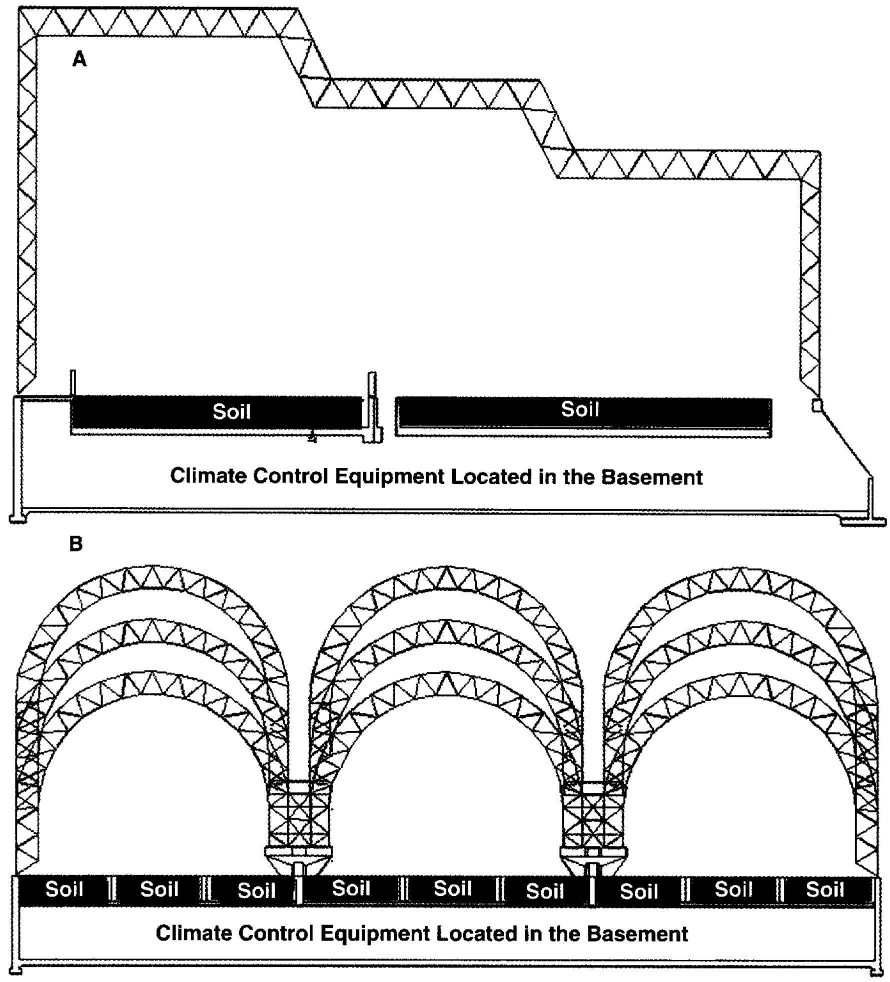


Figure 2. A sectional diagram of the intensive agriculture biome (IAB). A = east/west perspective, B = north/south perspective.

Presently, multidisciplinary ecological studies in the wilderness area are underway. Within the wilderness area, the soils during construction were well documented and constructed with the intent of simulating soil conditions for each ecosystem. In the IAB, studies have been initiated to determine the capability of the facility to maintain environmental control of temperature, humidity, and atmospheric content of O_2 and CO_2 in the three separate areas. However, very pragmatic food production objectives guided the selection of the initial IAB soil. The pertinent question addressed in this study was: Is this soil adequate and desirable for conducting global change research?

Biosphere 2 IAB Structure

The IAB (Figures 2 and 3) was constructed with two main purposes: 1.) to provide food sufficient for the sustenance of the human inhabitants, and 2.) to serve as a "soil bed reactor" to purify the air of trace gas contaminants resulting from outgassing of structural materials, plants, and humans (Nelson et al. 1993, Hodges and Fry 1990). The function of the IAB as a soil bed reactor dictated that the soil be rich in organic matter to support a diverse group of microbiota capable of metabolizing the trace gasses. This need for an organic rich soil base, as well as for providing the nutritional needs of the crops, explains the high levels of organic matter mixed with the soil at the time of construction. In addition, it explains the two tiered structure of the IAB (Figure 2).

The IAB consists of two floors, the first floor is the soil bed and a basement that houses the air and water handling equipment as well as a food processing area.

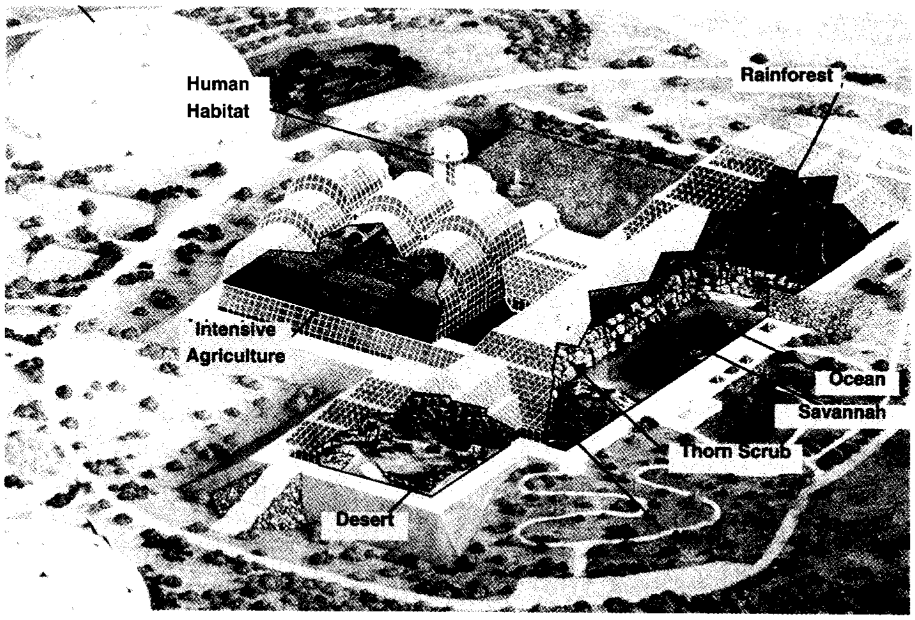
The floor of the soil bed consists of closely spaced cinder blocks which can allow air to be pumped through the bottom of the soil bed and then flow upward through the soil. The entire volume of air inside Biosphere 2 could be pumped through the soil bed reactor in approximately a 24 hr period (Nelson et al. 1993).

The glass dome above the soil bed

reaches a maximum height of approximately 24 m, with an atmospheric volume of 38,000 m^3. Light measurements through the glass dome of the IAB found a transmittance between 45–50% natural light levels, with the lower measurements attributed to the geometry of the space frame elements. The light levels inside the IAB had daily PAR levels of about 15 mol m^{-2} day^{-1} in winter and about 35 mol m^{-2} day^{-1} in summer, with virtually no UV radiation component.

The area covered by soil in the IAB is approximately 2,000 m^2, which was subdivided into 18 plots for food production, a banana (*Musa acuminata* Colla) area located along the north wall, and an elephant grass (*Penmisetum purpureum* Schum.) area (for animal feed production) located between the north and south plot areas (Figure 3). The elephant grass and banana belts were permanent features of the IAB during closure. Two of the plots (plot 1 and 10) were flooded for rice production.

After closure of Biosphere 2, a wide variety of food crops (90 different crops) were grown in the 18 pots of the IAB. However, because the most successful crops for food production were beets (*Beta vulgaris* L), sweet potatoes (*Ipomoea batatas* L Lam), and lablab bean (*Dolichos lablab* L), these three crops were produced in 65% of the IAB during closure. Rice was grown in plots 1 and 10 each year. In 1995–1996, after opening, a Yecora Rojo wheat (*Triticum aestivum* L) was grown in all plots of the IAB to assess growth patterns under 450 pppmv CO_2. Differences were observed in wheat yields across the IAB with the main variance being attributed to differences in light patterns across the plots. These data were utilized to designate yield potentials of the plots for soil analysis.



The Biosphere 2 complex. The environment is controlled for environmental conditions.

Three bays. The IAB is now separated into three different bays which can be independently controlled for environmental conditions, including temperature, humidity and atmospheric CO_2 concentration. The IAB was constructed with several independent air handling machines in the basement. This allows for environmental control of the bays by physical separation with two curtains that run north and south to separate the atmosphere and two walls installed to separate the soil across the IAB (Figure 2).

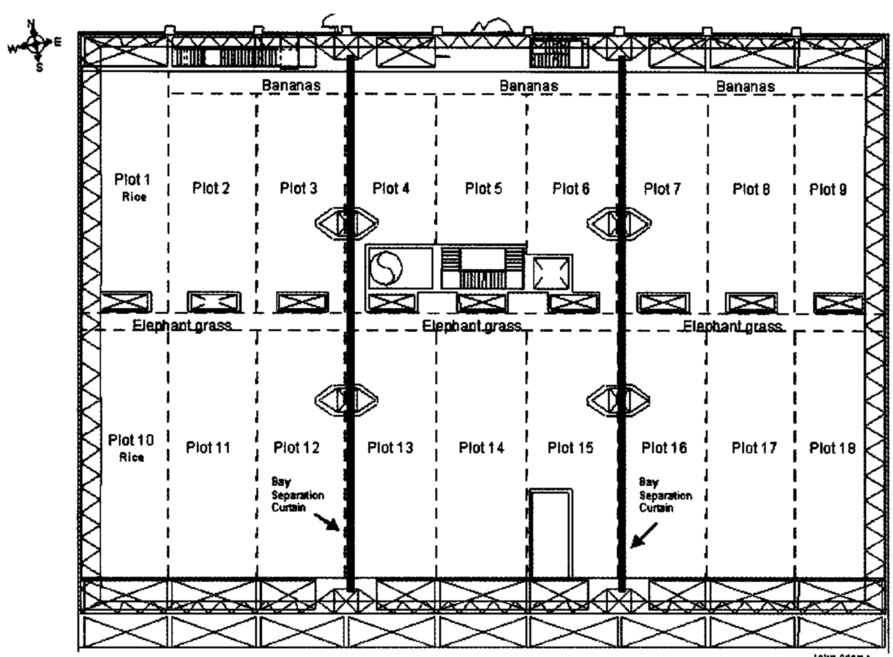


Figure 3. A floor map of the intensive agriculture biome (IAB), showing permanent structures, the agricultural plots, the rice plots, the banana belt, and the elephant grass belt. Also indicated is the location of the experimental bays.

Soil processes. In 1996, soils in Biosphere 2 had been in place for > 5 yr and undergone soil forming processes that are highly relevant not only as baseline data for continued research but also for answering questions of C sequestration. The initial loading of the soils with compost and peat moss and the subsequent mineralization of these materials under different crops and management activities provides an opportunity to study basic soil organic matter dynamics. Since these soils have existed for five years under different cropping systems with elevated CO_2, examining changes in the soil profile and between cropping systems may give important information regarding basic soil C and N dynamics and soil formation processes under elevated atmospheric conditions. Consequently, soil samples were collected to both develop a baseline of basic soil properties for possible future experiments and to examine pedogenic changes since the soils were installed.

Materials and Methods

Full profile soil samples were collected from the center of the 18 agricultural plots, with additional samples collected from each of the two rice plots. In addition, multiple soil samples were collected from the banana and elephant grass areas. Soil samples were collected using a hand driven soil sampler of 3.8 cm diameter and pushing the sampler to the floor of the IAB soil bed at each sampling location. Because the soil of IAB has settled from the original 120 cm depth, the depth of each soil sample taken was measured following soil sample removal. Actual soil depth ranged from 88–110 cm with an average depth of 96 cm. The soil samples were divided into four equal soil depth increments of approximately 0–25, 22–50, 50–75, and 75–100 cm and analyzed for soil physical and chemical properties.

Soil samples were dried (60° C), ground to pass a 0.15 mm sieve, and analyzed for total N and total P content colorimetrically on a Technicon Autoanalyzer (Technicon Instruments Corp., Tarrytown, NY), following digestion by a salicylic acid modification of a semimicro-Kjeldahl procedure (Bremner and Mulvaney 1982). Soil NO_3-N and NH_4-N concentrations were determined by extraction with 2 M KCl and measured by standard colorimetric procedures (Keeney and Nelson 1982) using the autoanalyzer. Soil organic C concentration was determined by two methods. Soil organic C and $CaCO_3$ concentration were determined by methods of Chichester and Chaison (1992) using a LECO CR12 Carbon Determinator (LECO Corp., Augusta, GA). In addition, soil organic C concentration was determined with a elemental analyzer (Isotope Services, Inc.; Los Alamos, MN) after pretreatment with HCl to remove $CaCO_3$. Organic C concentration between the two analysis methods were in close agreement, so average soil organic C concentrations between the two methods are presented here.

Soil samples were also analyzed for extractable concentrations of Ca, K, Mg, P, Cu, Fe, Mn, Zn, Mo, Al, Ba, Co, Cr, Pb, and Na by the Soil Testing Laboratory at Auburn University using procedures outlined by Hue and Evans (1986). The soils were extracted using a double acid or Mehlich 1 extractant (Mehlich 1953) and measured by inductive coupled plasma spectrophotometry (ICP 9000, Thermo Jarell-Ash Corp., Franklin, MA).

Acid washed soil samples were measured for $\delta^{13}C$ content after combustion in an elemental analyzer (Isotope Services, Inc.; Los Alamos, MN). Isotopes of C, with $\delta^{13}C$ are defined as

$$\delta^{13}C = \left[\frac{{}^{13}C/{}^{12}C_{sample} - {}^{13}C/{}^{12}C_{standard}}{{}^{13}C/{}^{12}C_{standard}}\right] \times 1000$$

Soil bulk density was determined on each soil core by calculating total soil dry weight within the volume of each soil core. In addition, soil bulk density was calculated from soil clods excavated from the center of the IAB using the clod method (Blake and Hartge 1982). Particle size analysis was determined by soil depth on selected soil cores using procedures of Gee and Bauder (1982).

During the Biosphere 2 closures, only recycled water was used for irrigation. Salt levels in the water rose leading to concerns about increasing soil salinity levels. The IAB soil was flushed with water (from 32 .1–150.8 m^3 depending on salinity levels) in September through October of 1995. Soil samples were collected from 0–33, 33–66, and 66–100 cm depth increments before and after flushing and measured for electrical conductivity (EC) of a saturated paste (Rhoades 1982). Soil pH (McLean 1982) was also measured from these soil samples.

Soil samples were analyzed by comparing the three areas to be utilized in new scientific studies (Figure 2), which would assess the potential use of this soil for future studies, and by comparisons between areas where cropping systems varied during the five years of Biosphere 2 closure. For this latter comparison, the 18 agricultural plots were separated based on grain yield measurements of the 1995–1996 wheat production.

The yield potential of the plots were divided into three groups: low (15–30 kg m2), medium (30–45 kg m^2), and high (45–60 kg m^2) yield. These areas corresponded to differences in light intensity measurements made at the IAB soil surface. The flooded rice plots were considered separately from the other agricultural plots, and soil samples from the elephant grass and the banana areas were included in the analysis. In addition, analyses for organic C, total N, and $\delta^{13}C$ concentration were performed on archived soil and plant samples from the initial closure to provide information for assessing pedogenic processes during the life course of Biosphere 2.

Statistical analysis of data was performed using the GLM procedure and means were separated using contrast statements and least significant difference (LSD) at an a priori 0.05 probability level (SAS 1985).

Results and Discussion

The soil of the Biosphere 2 IAB is classified as a silt loam soil (Gee and Bauder 1982), with an average of 27.8% sand, 54.4% silt, and 17.8% clay content. The average bulk density of the soil measured from each soil core was 1.1 g cm^{-3}. Soil bulk density measured at several depths with the clod method averaged 1.3 g cm^{-3}, with no differences observed between depths. This soil bulk density is relatively low for production agriculture soils and indicates that the soil has maintained a good tilth and has not been compacted with foot traffic. No evidence of an anoxic layer at the bottom of the biosphere IAB was observed, indicating that drainage of the IAB soil bed floor was satisfactory.

Analysis of electrical conductivities data indicated that, due to the use of recycled water during closure, the salinity levels in the IAB had become elevated, especially in the east and west bays (Table 1). Differences observed among initial EC levels were most likely a result of different watering regimes for crop production during Biosphere 2 closure. The EC levels measured in these two bays were elevated to levels that could explain the yield reductions noted in many crops (Hanson 1990). The soil flushing of the IAB was very effective at both, reducing the soil EC levels to a degree where no impact to crop production would be expected and equalizing the soil salinity levels so that no significant difference was observed among bays. Soil pH measurements made at this time also indicated that the pH levels of the soil were very consistent both by depth and across bays. Soil pH measurements had an average of 7.3, which is in the range were no response is expected from lime additions, and the soil plant availability of micro nutrients is maximized (Hanson 1990).

Table 2 shows the soil concentrations of nutrients essential for plant growth extracted from the soil of the IAB. The soil concentrations of other extractable elements are given in Table 3. Soil extraction techniques were aimed at determining the level of nutrients that will be plant available during the growing season. All macro and micro plant nutrients were found at levels sufficient to supply the above ground plant nutrient contents of a 9,416 kg ha^{-1} corn crop (Hanson 1990). Some differences in the macro and micro plant nutrients were noted between the experimental bays, with the west bay different compared to the other two bays (Table 2).

These differences were for both decreased (Ca, K, Mg, and B) and increased (P, Cu, Fe, and Mn) plant nutrients in the west bay. No significant difference (except for Co) was observed between the experimental bays for extractable elements that were not plant essential, indicating that

Table 1. Soil electrical conductivities (EC) measured before soil flushing and EC and pH after soil flushing in each experimental bay, averaged over soil depth.†

	Before Flush	After Flush	
Bay	(EC)	EC	pH
	----------- S m^{-1} ----------		
East	0.42a	0.13a	7.3a
Middle	0.41a	0.12a	7.3a
West	0.28b	0.13a	7.3a

† Columns followed by the same letter are not significant at the 0.05 level.

Table 2. Soil concentrations of soil extractable plant nutrients in each experimental bay, averaged over soil depth.†

Bay	Ca	K	Mg	P	Cu	Fe	Mn	Zn	B	Mo
	---------- ($g\ kg^{-1}$)	----------	----------	----------	----------	---------- ($mg\ kg^{-1}$)	----------	----------	----------	----------
East	4.17a	0.75a	0.40a	89.0a	1.1a	24.4a	84.3a	5.2a	3.0a	0.2a
Center	4.25a	0.74a	0.40a	78.9a	0.9a	20.7a	89.5a	5.4a	3.1a	0.2a
West	3.44b	0.61b	0.35b	92.6a	3.6b	55.9b	93.8a	5.0a	2.6b	0.2a

† Columns followed by the same letter are not significant at the 0.05 level.

the differences observed may likely be a function of biological changes in the soil from crop production. However, careful analysis of the data indicated that most of the differences observed could be attributed to the two plots which were flooded for rice production and, therefore, may have resulted from the physical and chemical changes due to flooding.

The observed changes to soil plant nutrients, while significantly different, were relatively small compared to differences commonly measured in production fields. Since these differences are not likely to cause plant growth limiting conditions, they should not interfere with plant production for experimentation. Analysis of a subsequent grain sorghum (*Sorghum bicolor* L Moench) crop that had been planted uniformly across the IAB indicated that plant nutrients were within the sufficiency range (Mills and Jones 1996) for plant production (unpublished data). However, this difference in soil nutrient levels should be noted as baseline for all future experimentation which includes interpretation of plant nutrition.

The soil concentrations of organic C, total N and P, and C:N ratios are much more important for interpretation of the global change research which is planned for the Biosphere 2 IAB by Columbia University (Vogel 1998; Vergano 1996). When averaged across plots in each experimental bay, no significant differences were observed in these measures among the experimental bays of the IAB up to a 0.10 probability level. However, differences were observed for inorganic N concentration among the experimental bays, with the inorganic N concentrations relatively high. Differences were also observed among cropping systems, which indicates that careful attention should be paid to the baseline soil data when interpreting future global change experimentation.

Because large amounts of organic C were added to the IAB soils when installed, an important question in evaluating the suitability of the IAB soil for global change research is, "How representative is the soil organic C and total N concentrations to natural soil ecosystems?" Initially (as determined from archived soil samples) the organic C concentration was 38.4 g kg^{-1}. This level of organic C is relatively high for many mineral soils used for agricultural production (Stevenson 1994), but it is not uncommon for soils found in the northern portion of the Corn Belt. Organic C levels of 50–60 g kg^{-1} are common in undisturbed prairie soils. However, the C:N ratio of 16 calculated for the archived soil samples (1991) is higher than is found in mineral soils and indicates that the soil C levels in 1991 were in a highly unsteady state.

During Biosphere 2 closure, release of CO_2 through soil respiration greatly outstripped plant uptake of CO_2 through photosynthesis (Severinghaus 1994), resulting in a reduction of soil organic C levels and elevated CO_2 concentration in the Biosphere 2 atmosphere. Soil samples measured in this study indicated that the soil organic C and C:N ratio had dropped, with an overall average organic C concentration of 24.0 g kg^{-1} and a C:N ratio of 12. This lower level of organic C is commonly found in production agriculture soil systems, and the C:N ratio indicates that the soil has relatively stable C and N cycling.

Differences were observed among depths for plant nutrients in the soil of the IAB, but no significant differences among depths were observed for the other soil extractable elements measured, except Ba. These differences were indicative of normal soil formation processes with soluble nutrients moving down in the soil profile with water movement, and plant mining of plant nutrients enriching the soil surface. As water moves downward in the soil, many of the soluble elements also move downward with the wetting front. Counteracting this soil physical process is the active extraction of plant nutrients with plant growth, much of which is utilized by the aboveground portion of the plant and then redeposited on the soil surface with plant residues (and compost additions). This plant mining process is typified by P, which is relatively insoluble in water but is taken up by plant roots and deposited near the soil surface in plant residues. The result is a gradient of soil P deceasing with increasing depth. Likewise, because plant root activity is concentrated near the soil surface, organic C levels were increased at the soil surface.

The plant nutrient stratification observed in IAB soils is a fundamental soil characteristic of soil profiles, generating the basic differences for which soil types are classified. The development of this stratification in the Biosphere 2 is an indication that normal soil formation processes are taking place, which is a giant step forward from studies of global change using restrictive pots. Therefore, the soils of the IAB provide an exceptional opportunity to study basic soil processes under highly controlled conditions. The challenge of understanding the dynamics of soil processes in a changing environment has great significance for coping with anticipated changes in the global atmospheric CO_2 concentration (Bolin 1986).

Global change. The present goal of Columbia University is to utilize Biosphere 2 to primarily further understanding of changing temperatures and increased atmospheric CO_2 concentrations on different ecosystems (Vogel 1998; Vergano 1996). The uncertainty of the global C cycle has been identified as a critical research issue for the national global change research effort (Lawler 1998). Studies already underway in the wilderness biomes have shown that changes in ocean carbonate concentrations resulting from elevated atmospheric CO_2 may damage coral reefs (Pennisi 1998).

While no comparative controls exist, the unique history of Biosphere 2, regarding a great increase in atmospheric CO_2 concentration compared to ambient air during closure, provides some important implications for global change effects on belowground processes that can be made by careful analysis of the soil in its present condition.

Table 3. Soil concentrations of selected soil extractable elements in each experimental bay, averaged over soil depth.†

Bay	Al	Na	Ba	Co	Cr	Pb
	------ ($g\ kg^{-1}$)	------	--------------- ($mg\ kg^{-1}$)	---------------		
East	0.17a	0.11a	3.0a	0.9a	0.4a	0.8a
Center	0.14a	0.15b	3.0a	0.9a	0.3a	0.7a
West	0.13a	0.09a	3.0a	1.4b	0.3a	1.0a

† Columns followed by the same letter are not significant at the 0.05 level.

Due to the organic matter additions to the soil, organic C concentrations in the IAB approached those found in the surface layers of undisturbed prairies, and the level of organic C was reduced during crop production. Because this reduction occurred under greatly elevated atmospheric CO_2 concentrations and under different soil management systems (i.e., cropped, grass, rice), analysis of the soil should allow for the examination of the effects of management systems on C sequestration from a unique perspective.

The initial soil mixture was very uniform compared to natural soils, which should have eliminated any inherent differences in soil comparisons, as is the usual case when comparing soils from adjacent areas under different management systems. Also, changes in the soil organic C levels can be very slow depending on climate conditions (Potter et al. 1998), and in most cases takes decades before detectable changes can be observed. Because the soil was initially high in organic C and stabilization occurred from high to lower levels, differences among management systems should be more easily detected.

Finally, research shows that plant material grown under elevated atmospheric CO_2 changes the decomposition processes in soil (Torbert et al. 1995; Torbert et al. 1997; Torbert et al. 1998). Because plant production occurred under greatly increased atmospheric CO_2 concentration, the decomposition of plant additions in Biosphere 2 should be reflective of conditions expected in the future as atmospheric CO_2 continues to rise.

Soil humus. These organic C additions would not be the same as soil humus that develops during the thousands of years of soil formation. Humus is composed of organic matter in different stages of decomposition resulting in a complicated mixture of organic compounds in a continuum of oxidation states and molecular weights (Stevenson 1994). In addition, the humus formed during soil formation is also inseparably connected with the soil structure, becoming an intricate part of soil aggregates (Stevenson 1994). However, because both the compost and the peat moss were highly decomposed organic material resistant to further decomposition, the organic matter additions used in the Biosphere 2 IAB were likely the best choices available for duplicating the complicated chemical structure of humus.

The plant residues in Biosphere 2 were initially composted and returned to the soil, however, as a result of the elevated atmospheric CO_2 concentration in Biosphere 2, the composting was suspended in the wilderness biomes to reduce further contributions of CO_2 to the atmosphere. It is not clear how much of the crop residue in the IAB was returned to the plots through compost during closure.

Management system's effects. The effect of a management system on soil concentration of organic C, total N, total P, C:N ratio, and δC^{13} (Table 4) show significant differences due to changes in the management systems. The total P in soil was significantly higher in the high yield plots and was significantly lower with rice. The soil organic C data showed a significant difference among the different management systems, with the organic C concentration highest in the grass plots compared to the banana trees, and lowest with the rice. There was little disturbance of the soil with elephant grass, but aboveground biomass was removed for animal feed. With banana trees there was extensive aboveground biomass production as the stalk was removed and there was regrowth from the roots, but there would have been little soil disturbance and much less biomass production and turnover in the roots.

There was a small non significant trend for organic C to follow the yield gradient of the plots. The rice plots were clearly affected differently compared to the other agricultural plots, including changes to the other macro and micro nutrient levels. These results could be due to lower biomass production with rice and changes to the soil resulting from flooding, including losses of soluble C and N with water movement. These data clearly indicate that changes in the production system will be a dominate factor in the amount of C that the soil can sequester.

The soil organic C concentration had a decreasing gradient with soil depth. The greater C losses from soil with increasing depth were likely the result of favorable soil moisture and aeration conditions for microbial organic C decomposition due to low soil compaction, coupled with a

One of the environments inside the Biosphere.

reduction in new organic C inputs with increasing depth. The δC^{13} concentration of soil organic C were near the levels of the Wilson pond at the 75–100 cm depth, but were more negative near the surface. In fact, the δC^{13} levels were more negative wherever soil organic C content was elevated above average. This indicated that the soil organic C cycling was stabilizing, with plant biomass additions and decomposition processes dominating the C cycling processes and not just C losses from the decomposition of the initial organic matter additions.

Significant differences. Significant differences were observed in the levels of total N following the same trends as soil organic C. This resulted in a very consistent C:N ratio. According to theory, the C:N ratio of plant biomass addition in Biosphere 2 would be expected to be high since all of the plants were grown under elevated CO_2, and archived plant tissue samples had C:N ratio at levels commonly reported for materials grown under these conditions. In addition, the initial C:N ratio of the soil was high, with an average of 16. However, because the soil organic C levels dropped abruptly in the IAB, there was no indication of slow decomposition rates. The initial soil N level was low in the soil as expressed by a high C:N ratio, but was elevated in total N concentration compared to the levels presently in the soil, which indicates that N was not a limiting factor for the decomposition of

Table 4. Effect of previous plant production on soil concentration of organic C, total N, total P and C:N and δC^{13}, averaged across soil depth.†

Crop	Organic C	Total N	Total P	C:N Ratio	δC^{13}
	($g\ kg^{-1}$)				‰
High yield	25.7a	2.30a	0.17a	12.1a	-23.2ab
Medium yield	24.7ab	2.13a	0.16b	12.2a	-23.1ab
Low yield	25.0ab	2.23a	0.16b	12.0a	-23.1b
Rice	20.8c	1.76b	0.14c	12.2a	-22.6c
Banana	23.4b	2.07a	0.16b	12.3a	-23.0b
Grass	26.2a	2.30a	0.16b	13.0a	-23.4a

† Columns followed by the same letter are not significant at the 0.05 level.

the original organic matter.

The C:N ratio of soil approaching equilibrium normally falls between 9 and 12, with a level of 10 the most commonly reported (Stevenson 1994). The C:N ratio of the IAB soil averaged 12 within the range reported, but higher than the C:N ratio of 9 observed in the original Wilson pond soil. Because of a reduction in the total N concentration observed in the soil and a high concentration of inorganic N, the observed soil C:N ratio would not likely be the result of N limitations. In fact, if the C:N ratio was calculated with the present level of organic C concentration and the original N concentration, the C:N ratio would be approximately 10. This indicates that the soil had stabilized at a higher C:N ratio than might be expected.

The C:N ratio of the rice plots were consistent with those found in the other management systems even though the soil organic C concentrations were significantly lower compared to the other management systems. In the rice, the total N level was also significantly lower compared to the other management plots, likely the result of both increased N loses with water movement through the soil and increased denitrification losses of N to the Biosphere 2 atmosphere.

The high N_2O levels reported for the Biosphere 2 during closure (Broecker 1996) are consistent with significant levels of denitrification occurring in the soil. The N loss mechanism would clearly be different in the rice plots compared to the other plots that were not flooded. The result was a significantly lower soil organic C and total N concentrations, but an almost identical C:N ratio. This indicates that the observed C:N ratio was very stable, and different from that measured in the original Wilson Pond soil. Further, these data indicate that soils with plant biomass inputs grown under elevated atmospheric CO_2 may seek a higher equilibrium C:N ratio than is presently found in soils, resulting in higher C contents with the same N content. Therefore, these data also imply that with elevated CO_2, an increased level of soil C sequestration may result as the level of atmospheric CO_2 increases.

Due to the practice of water recycling which resulted in irrigation water that was highly enriched in NH_4 and NO_3, potential changes in N cycling can not be addressed in the present analysis of Biosphere 2. This N enrichment of water would have eliminated any impact of N limitations in the soil, and therefore limited the implications for the importance of N cycling on global change in many ecosystems. However, if this phenomenon was due to the initial high organic matter in soil, then it may indicate what might be expected in a future elevated CO_2 world in ecosystems with high organic matter soils. Regardless, soil organic C concentrations were different with depth and among management systems, indicating that changes had taken place in soil C storage independent of N limitations in soil. Any shift in soil C:N ratio could not be due to N limitation and, therefore, reflect a fundamental change in the characteristic of the soil organic matter. From a global perspective, this indicates that the question of C in soil can not be fully addressed from a balance sheet of C and N inputs. Rather, the potential changes in plant biomass quality and management systems must also be considered.

The data for the IAB soil provide two important implications for global change to soil. First, the management systems will be a dominate factor in potential soil C sequestration, and second, soil organic C content may change due to changes to biomass and the resulting changes in decomposition. Shifts in soil C:N ratio may result in increased levels of C in soil even with the same level of N, most often limiting in ecosystems. With the experimentation planned for Biosphere 2, data should become available that will provide more definitive evidence of changes in soil C and N cycling as affected by phenomena associated with global change scenarios.

Acknowledgments

The authors are indebted to Tilak Mahato and John Adams of the Biosphere 2 Center/Columbia University for technical assistance during this study.

Disclaimer

Products mentioned in this study are not an endorsement of the product, but identification of the specific product used for the study.

REFERENCES CITED

Blake, G.R. and K.H. Hartge. 1982. Bulk density. Pp. 363-375. In: A. Klute et al. (eds). Methods of soil analysis: part 1. Madison: American Society of Agronomy and Soil Science Society of America. Agronomy Monograph 9.

Bazzaz, F.A. 1990. The response of natural ecosystems to the rising global CO_2 levels. Annual Revue of Ecological Systems 21:167-196.

Bolin, B., B.R. Doos, J. Jager, and R.A. Warrick. 1986. Scope 29—the greenhouse effect, climatic change, and ecosystems. Chichester: John Wiley & Sons.

Boutton, T.W. 1991. Stable carbon isotope ratios of natural materials: I. sample preparation and mass spectrometric analysis. In: D.C. Coleman &B. Fry (eds). Carbon isotope techniques. San Diego: Academic Press, Inc.

Bremner, J.M. and C.S. Mulvaney. 1982. Nitrogen total. Pp. 595-624. In: A.L. Page et al (eds). Methods of soil analysis: part 2. 2nd ed. Madison: American Society of Agronomy and Soil Science Society of America. Agronomy Monograph 9.

Broecker, W.S. 1996. The biosphere and me. GSA Today 6:1-7.

Chichester, F.W. and R.F. Chaison, Jr. 1992. Analysis of carbon in calcareous soils using a two temperature dry combustion infrared instrumental procedure. Soil Science 153:237–241.

Gee, G.W. and J.W. Bauder. 1982. Particle-size analysis. Pp. 383-411. In: A. Klute et al. (eds). Methods of soil analysis: part 1. Madison: ASA and SSSA. Agronomy Monograph 9.

Hanson, A.A. (Ed). 1990. Practical handbook of agricultural science. Boca Raton: CRC Press, Inc.

Holden, C. (Ed). 1996 Miniworld on the big screen. Science 271: 453

Hodges, C. and R. Fry. 1990. Soil bed reactor work of the Environmental Research Lab of Biosphere 2 project. Pp. 47-52. In: M. Nelson & G.A. Soffen (eds). Biological life support systems. Oriacle: Synergetic Press.

Hue, N.V. and C.E. Evans. 1986. Procedures used for soil and plant analysis by the Auburn University Soil Testing Laboratory. Auburn University: Department of Agronomy and Soils. Department Series No. 106.

Kaiser, J. (Ed). 1996 New manager for Biosphere 2. Science 273: 1327.

Keeney, D.R. and D.W. Nelson. 1982. Nitrogen – inorganic forms. Pp 643-696. In: A. L. Page et al. (eds). Methods of soil analysis: part 2. 2nd ed. Madison: American Society of Agronomy and Soil Science Society of America. Agronomy Monograph 9.

Lawler, A. 1998. Global change fights off a chill. Science 280:1682-1684.

McLean, E.O. 1982. Soil pH and lime requirement. Pp 199-224. In: A. L. Page et al. (eds). Methods of soil analysis: part 2. 2nd ed. Madison: American Society of Agronomy and Soil Science Society of America. Agronomy Monograph 9.

Mehlich, A. 1953. Determinations of P, Ca, Mg., K, Na, and NH4 by North Carolina soil testing laboratories. Raleigh: North Carolina State University.

Mills, H.A. and J.B. Jones, Jr. 1996. Plant analysis handbook II. Athens: MicroMacro Publishing, Inc.

Nelson, M., T.L. Burgess, A. Alling, N. Alvarez-Romo, W.F. Dempster, R.L, Walford, and J.P. Allen. 1993. Using a closed ecological system to study earth's biosphere, initial results from Biosphere 2. Bioscience 43:225-236.

Pennisi, E. 1998. New threat seen from carbon dioxide. Science 279:989.

Potter, K.N., H.A. Torbert, O.R. Jones, J.E. Matocha, J.E. Morrison, Jr., and P.W. Unger. 1998. Distribution and amount of soil organic carbon in long-term management systems in Texas. Soil Tillage Research 47:317-329.

Prior, S.A., H.A. Torbert, G.B. Runion, H.H. Rogers, C.W. Wood, B.A. Kimball, R.L. Lamorte, P.J. Pinter, and G.W. Wall. 1997. Free-Air CO2 enrichment of wheat: soil carbon and nitrogen dynamics. Journal of Environmental Quality 26:1161-1166.

Rabinovitz, J. 1995. Columbia to take over Biosphere 2 as earth lab. The New York Times November 13, 1995.

Rhoades, J.D. 1982. Soluble salts. Pp 167-180. In: A. L. Page et al. (eds). Methods of soil analysis: part 2. 2nd ed. Madison: ASA and SSSA. Agronomy Monograph 9.

Statistical Analysis System (SAS) Institute, Inc. 1985. SAS user's guide. Cary: SAS Institute, Inc.

Severinghaus, J.P., W.S. Broecker, W. F. Dempster, T. MacCullum, and M. Wahlen. 1994. Oxygen loss in Biosphere 2. EOS, Transactions, American Geophysical Union 75 (03):35-37.

Stevenson, F.J. 1994. Humus Chemistry, Genesis, composition, reactions. New York: John Wiley & sons, Inc.

Strain, B.R., and J.D. Cure, (Eds). 1985. Direct effects of increasing carbon dioxide on vegetation. Washington, D.C.: U.S. Department of Energy. Office of Energy Research No. DOE/ER-0238.

Torbert, H.A., S.A. Prior, and H.H. Rogers. 1995. Elevated atmospheric carbon dioxide effects on cotton plant residue decomposition. Soil Science Society of America Journal 59:1321-1328.

Torbert, H.A., S.A. Prior, H.H. Rogers, and G.B. Runion. 1998. Crop residue decomposition as affected by growth under elevated atmospheric CO2. Soil Science 163:412-419.

Torbert, H.A., H.H. Rogers, S.A. Prior, and W.H. Schlesinger. 1997. Elevated atmospheric CO2 in agro-ecosystems effects on soil carbon storage. Global Change Biology 3:513-521.

Torbert, H.A., S.A. Prior, H.H. Rogers, W.H. Schlesinger, G.L. Mullins, and R.G. Runion. 1996. Elevated atmospheric CO2 in agro-ecosystems affects groundwater quality. Journal of Environmental Quality 25:720-726.

Vergano, D. 1996. Brave new world of Biosphere 2? New operators of the desert greenhouse aim to save the planet. Science News 150:312-313.

Vogel, G. 1998. An institute for planet earth. Science 280:1182-1185.

Wolfgang, L. 1995. Biosphere 2 turned over to Columbia. Science 270:1111.